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THE MEAN FREE PATH OF ELECTRONS IN MERCURY VAPOR

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THE MEAN FREE PATH OF ELECTRONS IN MERCURY VAPOR

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Numerous investigators[1] have determined the nature of the scattering of electrons in many of the common gases and have interpreted their results in terms of the mean free path of the electron. The present article describes a method for measuring the mean free path of electrons and presents the results for mercury vapor for velocities ranging from a fraction of a volt to 3000.

We know from kinetic theory that for a beam of electrons moving through a gas

$$I = I_0 e^{-x/\lambda} \qquad (1)$$

where I_0 is the initial number of electrons in the beam, I the number which go a distance x without suffering a collision with a molecule of the gas and where λ is the mean free path. In order to apply this equation experimentally it is sufficient to insert a movable Faraday cage which can measure the current I_0 and then the succeeding values of I. In doing this the natural spreading of the beam must be considered. When there is no gas in the presence of the electrons, let K be the fractional part of the total number of electrons initially present in the beam which enter the cage opening for a certain position x. With this definition of K our above equation becomes

$$I = KI_0 e^{-x/\lambda} \qquad (2)$$

which presents a working formula. Having obtained K for a value of x

with the gas absent and having found I/I_0 for the same x with the gas present, λ can then be computed.

Figure 1 shows diagrammatically the apparatus and electrical circuit. Electrons from the heated tungsten filament F were sent through circular openings S_1, S_2, S_3 and S_4. S_1 and S_3 were 2 mm. in diameter and 2 cm. apart. S_2 was 4 mm. in diameter and midway between S_1 and S_3. S_4 was 1 mm. from S_3 and 4 mm. in diameter. Thus a beam of electrons was obtained in the equipotential region C_2. All of the electrons leaving S_3 were measured by galvanometer G_2. The Faraday cage C_1 was a complete absorber of electrons because of its extreme length 21 cm. and its width 4.5 cm. Circular openings D_1 and D_2 were of 14 and 12 mm. diameter, respectively. Therefore, once an electron passed through D_2 it was measured by galvanometer G_1 as is shown in figure 1. The cage was moved through a distance of 8 cm. by a windlass, and the scattering of the electrons from the beam would appear as a change of the current through G_1. The cage was made of copper, the other parts of iron, with the exception of a nickel gauze G, which decreased the reflection and secondary emission of electrons from the walls of C_2. Additional precautions were taken to reduce the presence of secondary electrons by nickel plating all of the metal parts, leaving the surfaces with a dull finish.[2] The parts were thoroughly outgassed in a vacuum furnace to remove all occluded gases.

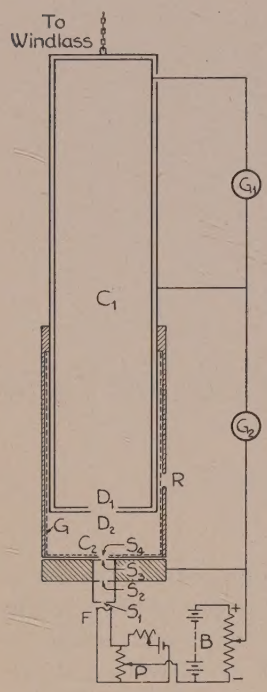

FIGURE 1
Apparatus and electrical circuit.

The position for $x = 0$ was taken when the cage was resting directly over S_4. Galvanometer G_1 gave the total number of electrons I_0 initially present in the beam. Simultaneously G_2 should have read the same as G_1, but generally indicated slightly more current than did G_1, because of a few electrons that would drift over to the edges of the opening S_4 and not enter C_2. In each instance the difference was noted so that G_2 could be read in terms of G_1 giving continually the term I_0 while at the same time I would be read by G_1 for six different settings of the cage (i.e., for $x =$ 3, 4, 5, 6, 7 and 8 cm.).

Figure 2 gives the velocity distribution of I_0 for accelerating potentials of 5, 10 and 40 volts, and shows more secondary electrons present for the 40 volts than for the other two voltages. This is due to the secondary emission from the edges of S_1 and the other openings.

With the pressure in C_2 less than 10^{-6} mm. Hg, the values of K were obtained for the various settings of C_1, and for the different accelerating potentials. The mercury vapor was then introduced at a definite pressure. The temperature of the tube containing the apparatus was kept at 27°C. and hence the pressure in the tube was that corresponding to this temperature which is 2.9 bars.[3] Because of the heating due to the filament the actual temperature of region C_2 was 75°C., with a slight temperature gradient from $x = 0$ to $x = 8$ cm. The mean free path of the mercury molecule was large compared to the openings leading from C_2 to the cooler part of the tube, so that the ratio of the pressures in the two parts is equal to the square root of the ratio of the absolute temperatures, which gives the pressure in C_2 as 3.12 bars. With this pressure and temperature the

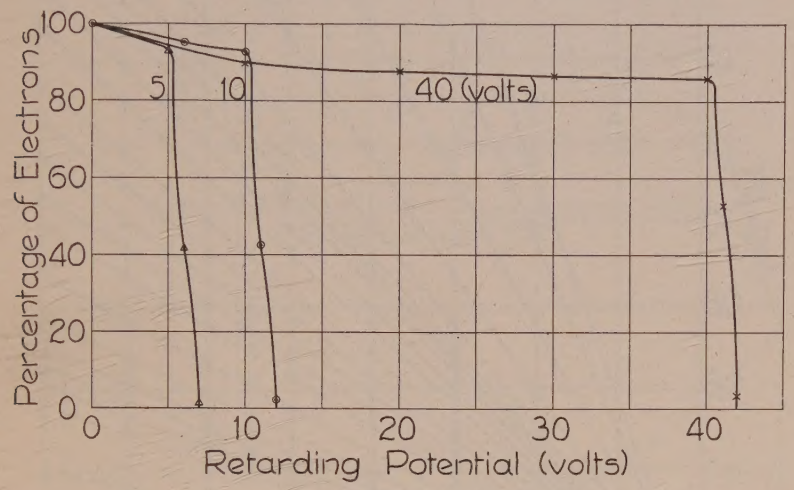

FIGURE 2
Velocity distribution of I_0.

ratio of I/I_0 was found. The order of magnitude of I_0 was 2×10^{-8} amperes, and variations of I_0 by more than 200% caused no change of I/I_0. The solution for λ was performed graphically by plotting $-\log_e(I/KI_0)$ with respect for x, and the inverse of the slope of the curve gave the mean free path.

Figure 3 shows $-\log_e(I/KI_0)$ plotted with respect to x for a number of velocities. It is noticed that the points form straight lines showing that there is a linear relation between $-\log_e(I/KI_0)$ and x, which is in accord with our equation (2). Because of the solid angle that is subtended by D_2 it would be possible for an electron after colliding to still pass through D_2 and be measured as having not collided. The magnitude of this effect can be calculated and it is found that it would cause an error of 1% in

the results shown in figure 3, which is approximately the order of experimental error.

Figure 4 gives the results found for the mean free path of the slow electrons at a pressure of 3.12 bars and temperatures of 75°C. A change in the direction of the curve occurs at 4.9 volts, and a very slight indication of a change in slope takes place at 6.7. The change at 4.9 is more notice-

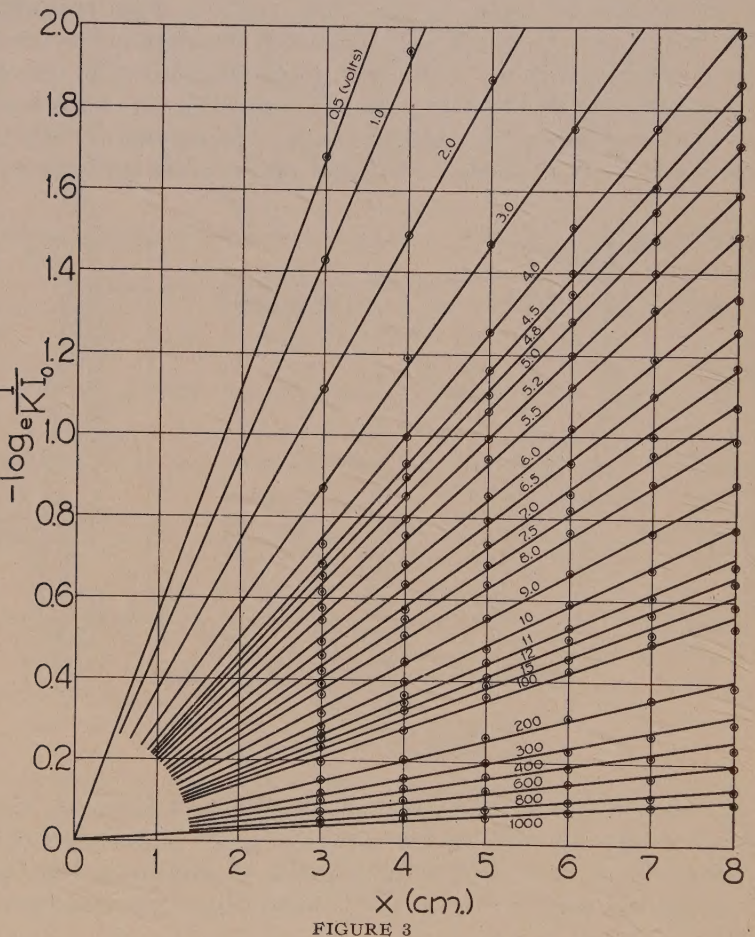

FIGURE 3

Showing linearity between $-\log_e\left(\frac{I}{KI_0}\right)$ and x.

able than that at 6.7, which is to be expected because the collision at 6.7 is known to be less prominent than at 4.9. This shows that the mean free path is affected by the type of collision which occurs at these critical potentials. Figure 5 is a continuation of figure 4 showing results for higher velocities. A decrease in the curve is found with a minimum at about 40

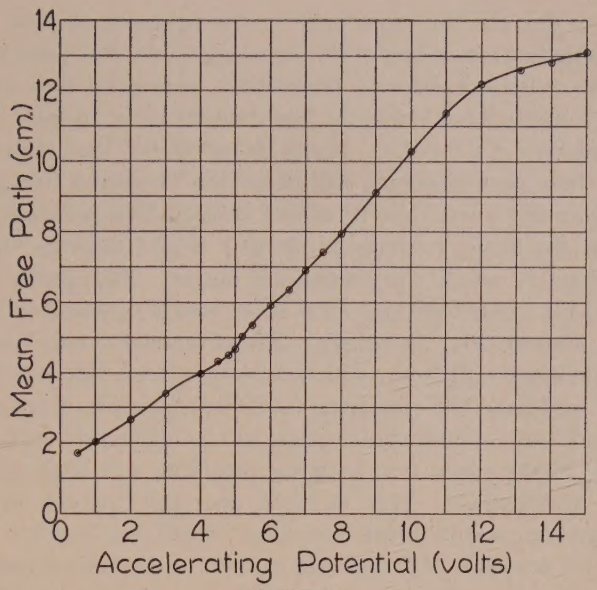

FIGURE 4

Mean free path for the lower voltages at pressure of 3.12 bars and temperature 75°C.

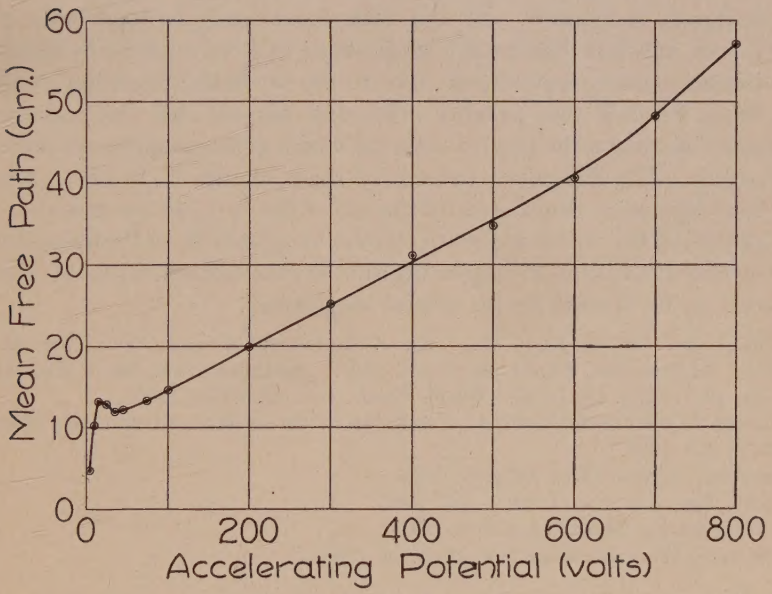

FIGURE 5

Mean free path for the higher voltages at pressure of 3.12 bars and temperature 75°C.

volts. This is due for the most part to the presence of slow secondary electrons coming from the edges of the openings S_1, S_2, S_3, S_4 and D_2. From figure 2 for 40 volts' accelerating potential it is noticed that about 15% of the total electrons have velocities less than 40 volts, in fact, 7.5% have an average velocity of 2.5 volts. It can be calculated that the short mean free path of these slow electrons will cause the measured free path at 40 volts to be about 8% lower than its actual value. This percentage of error will be less at the lower voltages as figure 2 would indicate, but at the higher velocities it would be somewhat larger. The mean free path was measured for 1120, 2040 and 3050 volts, and was found to be 73, 123 and 144 cm., respectively. λ calculated from kinetic theory for this pressure and temperature is 21.5 cm., which is that given for 230 volts in figure 5.

Brode[4] has measured the scattering coefficient for slow electrons in mercury vapor and found no unusual changes at the critical potentials, and no small increase of the mean free path for velocities less than one volt, as reported by Minkowski.[5] This increase does not appear in figure 4 which is in agreement with Brode's results. Changing Brode's coefficient of scattering for pressure of 1 mm. Hg at 0°C. to the mean free path for pressure of 3.12 bars at 75°C. it is found that his results are of the same order of magnitude as those given in figure 4. For example, he obtains 5 cm. for 4 volts which is compared with 4 cm. from figure 4. His results, however, for the higher velocities give a much longer mean free path than is shown in figure 5. At 100 volts his measurements would give $\lambda = 47.3$ cm. which is considerably larger than 14.5 cm. as given by figure 5. This disagreement is undoubtedly due to the secondary emission of electrons from Brode's two parallel disks and his circular ring collector. Lawrence[6] has shown the type of collector which gives complete absorption of electrons. The difficulties caused by space charge in Brode's experiment have here been eliminated by the use of the two galvanometers.

In conclusion the writer wishes to express his gratitude to Professor John T. Tate who in addition to suggesting this work rendered valuable advice and to Dr. J. W. Buchta for his helpful suggestions.

[1] Lenard, *Ann. Physik*, **12**, p. 714, 1903. Compton and Benade, *Physic. Rev.*, **8**, p. 449, 1916. Mayer, *Ann. Physik*, **64**, p. 451, 1921. Ramsauer, *Ibid.*, **64**, p. 513, 1921; **66**, p. 546, 1921; **72**, p. 345, 1923. Brode, *Physic. Rev.*, **25**, p. 636, 1925.

[2] For this method of diminishing secondary electrons see Hull and Williams, *Physic. Rev.*, **27**, p. 435, 1926.

[3] Langmuir, *General Electric Review*, 1924.

[4] Brode, *Proc. Roy. Soc.*, **109A**, p. 397, 1925.

[5] Minkowski, *Zs. Physik*, **18**, p. 258, 1923.

[6] Lawrence, *Proc. Nat. Acad. Sci.*, **12**, p. 29, 1926.

VITA

The author, Louis R. Maxwell, was born in Waterloo, Iowa, on May 28, 1900. He was graduated from Mount Vernon High School at Mount Vernon, Iowa, in June, 1918. In June, 1923, he received the Bachelor of Arts degree from Cornell College, Mount Vernon, Iowa, and the Ph.D. degree from the University of Minnesota in June, 1927. From 1923 to 1927 he was a Teaching Assistant in the Department of Physics at the University of Minnesota. He is a member of the American Physical Society, the Iowa Academy of Science, Gamma Alpha and was elected to Sigma Xi.